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Brief communication: On area- and slope-related thickness estimates and volume calculations for unmeasured glaciers

Haeberli, Wilfried

Abstract: Area- and slope-related techniques have been used to estimate thicknesses and to calculate volumes of unmeasured glaciers on the basis of glacier outlines and corresponding glacier surface areas in glacier inventories. The present communication critically reflects key aspects involved with the application of these approaches to field data. Area-related empirical statistics are known to only provide order-of-magnitude estimates if applied to individual glaciers or glacier ensembles spanning less than several orders of magnitude. Even at this scale, however, problems exist with respect to calibration/validation, error propagation, artefacts (immediate mass loss in case of coalescing/disintegrating composite glaciers) and shortcomings (no detection of ice below sea level or below lake levels on land in view of glacier contributions to sea-level rise). 3-D-flux/stress/slope-related approaches and numerical models are better constrained by calibration/validation with field measurements. They help with overcoming the problems of 2-D-area-related statistics in that they allow for calculating detailed glacier bed topographies at all scales, from individual glaciers to global ensembles. Corresponding results are available today and can be further improved.

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Brief communication: On area- and slope-related thickness estimates and volume calculations for unmeasured glaciers

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Area- and slope-related techniques have been used to estimate thicknesses and to calculate volumes of unmeasured glaciers on the basis of glacier outlines and corresponding glacier surface areas in glacier inventories. The present communication critically reflects key aspects involved with the application of these approaches to field data. Area-related empirical statistics are known to only provide order-of-magnitude estimates if applied to individual glaciers or glacier ensembles spanning less than several orders of magnitude. Even at this scale, however, problems exist with respect to calibration/validation, error propagation, artefacts (immediate mass loss in case of coalescing/disintegrating composite glaciers) and shortcomings (no detection of ice below sea level or below lake levels on land in view of glacier contributions to sea-level rise). 3-D-flux/stress/slope-related approaches and numerical models are better constrained by calibration/validation with field measurements. They help with overcoming the problems of 2-D-area-related statistics in that they allow for calculating detailed glacier bed topographies at all scales, from individual glaciers to global ensembles. Corresponding results are available today and can be further improved.

1 Introduction

Area-related thickness estimates and corresponding volume calculations for unmeasured glaciers have been used for decades (UNESCO, 1970; Müller et al., 1977). As a number of recent publications show (Andreassen et al., 2015; Martín-Español et al., 2015; Zekollari and Huybrechts, 2015), they are still frequently applied today. Such procedures, however, involve a number of shortcomings and the input data are limited to 2-D (planar) information, while alternatives using 3-D-topography (elevation, slope) have long been available (Haeberli and Hoelzle, 1995), more recently made striking progress in their application to DEM information as combined with glacier inventories (e.g., Huss and Hock, 2015) and provide more promising approaches. In particular,

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the possibility to model detailed glacier-bed topographies reaches far beyond coarse and highly uncertain values of “average thicknesses” or “total volumes” estimated by area-related approaches. Furthermore, average basal shear stresses used with, or calculated from, flux/elevation/slope-related approaches provide a robust and transparent possibility to test the plausibility of calculated values. The following briefly outlines key aspects involved concerning scatter and volume–area self-relation in statistical regression, area definition, error propagation, calibration/validation and limitation to 2-D information and average thicknesses. Model inter-comparison is recommended and the full use of available 3-D information is advocated.

2 Glacier areas, thicknesses and volumes

Glacier volumes V (unit: m^3) are calculated from information about glacier thickness obtained from numerical models or determined in the field using drillings or geophysical soundings at points or profiles and inter-/extrapolated, averaged or integrated over measured glacier areas A (unit: m^2). Corresponding technical procedures are described in recent studies by Andreassen et al. (2015) or Martín-Español et al. (2015). A modern database of glacier thicknesses and areas is available from the World Glacier Monitoring Service (WGMS; Gärtner-Roer et al., 2014). Glacier volumes determined using field measurements contain the defined glacier areas from which they have been calculated: $V = A \cdot h$, where h = mean glacier thickness (unit: m) over the defined area (cf. the definition in Cogley et al., 2011).

3 Area-related approaches

The use of 2-D- (planar) area-related statistics for estimating thicknesses and volumes of unmeasured glaciers is still common. In particular, the direct statistical correlation between glacier volumes and glacier areas (often called “volume–area scaling”) has become popular and is quite commonly considered to be the most simple and

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most widely used method to estimate volumes of large samples of glaciers (Zekolari and Huybrechts, 2015; cf. the long list of references provided in Table 1 of Bahr et al., 2015). However, approaches using 2-D- (planar) area-related information for estimating glacier thicknesses and deriving glacier volumes involve a number of shortcomings concerning scatter/uncertainty, area definition, error propagation and calibration/validation. Technical aspects involved with these shortcomings are summarized below.

3.1 Scatter/uncertainty

Empirical thickness–area (h – A) relations are characterised by a scatter of about half an order of magnitude for larger glaciers to an order of magnitude for smaller glaciers as illustrated in Fig. 1 (upper left; cf. Fig. 8.5 in Cogley, 2012; Fig. 7a in Andreassen et al., 2015; or Fig. 2 in Bahr et al., 2015). In addition to possible errors in field measurements of ice thickness and their interpretation, this very large scatter is most likely caused by the variability of glacier surface slopes (cf. Fig. 10 in Frey et al., 2014) and has been known for decades already (cf., for instance, Müller et al., 1976): area is not a good predictor of glacier thickness and, hence, of glacier volumes calculated from them. Corresponding correlations are often weak for glaciers $< 10 \text{ km}^2$, a power law hypothesis is difficult to assess with less than two orders of magnitude in ice thickness (as explicitly stated in the caption to Fig. 2 of Bahr et al., 2015; cf. also Fig. 7a in Andreassen et al., 2015), and basic problems exist for larger, mostly composite glaciers, as explained below. The model inter-comparison by Frey et al. (2014; see in particular their Fig. 10) document that area-related statistics tend to systematically underestimate thicknesses of flat glaciers and to systematically overestimate thicknesses of steep glaciers. Recognizing such problems at an early stage, UN- and ICSU-related international glacier monitoring (World Glacier Monitoring Service, WGMS, and its predecessor organisations) abandoned the provision of thickness/volume estimates derived from area-based statistics in the first World Glacier Inventory (WGMS, 1989; cf. also Müller et al., 1977)

and later developed a flux/stress/slope-related approach for application with regional glacier inventories (Haeberli and Hoelzle, 1995; cf. also Haeberli et al., 2007).

This policy is strongly supported by theoretical considerations about volume–area scaling for glaciers. Like the extensive review by Bahr et al. (2015), the literature on volume–area scaling theory emphasizes that power law scaling methods do not apply accurately to single glaciers but only to large ensembles of glaciers spanning several orders of magnitude, or, alternatively to single glaciers only at order-of-magnitude precision. Such limitations are, however, often misunderstood or even ignored. The development in the literature on the application side indeed goes in an opposite direction: area-related approaches are being applied to smaller and smaller glacier ensembles spanning lower and lower orders of magnitude. For example, calculations of global sea-level equivalents in glacier ice are broken down to variable but also small glacier ensembles (Radić and Hock, 2011), the regional study on Norwegian glaciers by Andreassen et al. (2015) comprises a glacier ensemble of essentially two orders of magnitude, and Zekollari and Huybrechts (2015) even fit regression parameters to one single glacier (Morteratsch in the Swiss Alps) and its changes in time. The application of area-related estimates for glacier changes in time involves additional problems and artefacts as explained below.

Replacing the glacier thickness–area relation by direct statistical correlations between glacier volumes and areas (Bahr et al., 1997, 2015; Andreassen et al., 2015) adds no new information but is still exactly the same empirical-statistical area-related approach. The only change is that the thickness–area (h – A) regression is now mathematically transformed into a self-regression between glacier volumes ($V = A \cdot h$) and the glacier areas (A) from which these volumes had been calculated. This is not usually made clear in the corresponding papers. Scientific arguments for justifying the transformation of a regression into a self-regression are not provided and the added value of this procedure remains obscure. The key disadvantage, however, is obvious: the large uncertainty in the relation between the glacier thickness/area data is seemingly suppressed. Unrealistic degrees of statistical correlation (for instance, $R^2 = 0.99$ in Bahr

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et al., 1997) are calculated providing a false impression of the origin and quality concerning the field data used and their interrelationship. Figure 1 (upper right) illustrates the problem (cf. also the Figs. 2 and 1 – best in this sequence – of Bahr et al., 2015, or the Figs. 7a and b in Andreassen et al., 2015). The use of glacier area in both variables of the statistical regression (and in both axes of the corresponding scatter plots) artificially increases squared correlation coefficients (from $R^2 = 0.6802$ to $R^2 = 0.9684$ in the example provided by Bahr et al., 2015 in their Figs. 2 and 1, from $R^2 = 0.57$ to $R^2 = 0.92$ in the Figs. 7a and b in Andreassen et al., 2015, or from $R^2 = 0.8343$ to $R^2 = 0.9731$ for the numerically modelled glaciers in Fig. 1) and produces seemingly good-looking (often log-log) diagrams. Related predictive equations like

$$V = A \cdot h = c \cdot A^\gamma \quad (1)$$

(with c and γ as regression parameters) essentially calculate glacier area from itself. The discussions about locally/regionally different V – A regression parameters provided in many papers indeed still directly concern the thickness–area relation, which contains exactly the same information from field data. The transformation of this relation into a volume–area self-relation for quantitative predictions is an unnecessary and even misleading detour.

3.2 Area definition

Glacier area can be ill-defined for many reasons (especially in connection with snow cover, shadow, flat firn divides, debris cover, etc.). The problem is particularly severe for large and complex composite glacier systems, where the thickness and volume estimated for the total area is systematically larger than the thicknesses estimated from the areas of individual components and the sum of the corresponding partial volumes because

$$(c \cdot A)^\gamma \neq c \cdot A^\gamma \quad (2)$$

(cf. the discussions in Andreassen et al., 2015 or Bahr et al., 2015). Corresponding artefacts (step functions of thickness/volume change) are immediately obvious with glacier complexes coalescing or disintegrating over time (Table 1). Such artefacts may be irrelevant in scaling theory but can be very large and are serious drawbacks concerning quantitative values derived from inventory data about real glaciers, especially in the case of the complex largest glaciers on Earth with their predominant influence on sea level (Meier et al., 2007).

3.3 Error propagation

Glacier areas are used to calculate volumes of glaciers. If the same glacier areas are also used to estimate mean glacier thicknesses from statistical regression, errors in area definition affect the estimated thicknesses over the entire glacier area as well. The corresponding errors are thus cumulative for volume calculations and increase the uncertainty even beyond the already large scatter recognisable in statistics and scatter plots of glacier thickness vs. glacier area. This problem is again especially serious with ill-defined areas of large composite glacier complexes, and hence, for estimating sea-level equivalents. In connection with sea-level studies, area-related approaches have an additional problem: they cannot detect the non-negligible parts of glacier ice that do not contribute to sea-level rise because they are already below sea level or below the level of new lakes forming in glacier-bed overdeepenings, which become exposed as a consequence of ongoing glacier disappearance (cf. Haeberli and Linsbauer, 2013; Huss and Hock, 2015).

3.4 Calibration/validation

Estimated average values of glacier thickness, or of total values for glacier volumes, can only be compared to corresponding values derived from inter-/extrapolated thickness data, which are again not “measured” but are products calculated using sometimes unknown or questionable assumptions. They can therefore not be directly calibrated or

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validated with thickness information from field measurements. This is quite serious as field information for logistic reasons tends to be biased towards accessible crevasse-free flat zones, where glaciers tend to be relatively thick.

3.5 Average thickness

By definition, area-related estimates can only provide average values of glacier thicknesses. Further refinement of such coarse average information to provide more detail on thickness variation for individual ice masses requires 3-D-information to be used. This important step opens another dimension of research into glacier geometry. Corresponding possibilities have existed for some time with the use of flux/stress/slope-related approaches.

4 Slope-related approaches

Flux/stress/slope-related approaches (assuming a constant basal shear stress and relating ice thickness to surface slope) for estimating the thicknesses of unmeasured glaciers are probably as old as, if not even older than, area-related statistics (e.g. Paterson, 1969). An important step in the advancement of such procedures was the recognition that average basal shear stress is not the same for all glaciers (sometimes assumed to be “1 bar” = 100 kPa) but systematically depends on the mass turnover determined for each glacier by its size (elevation range) and mass balance gradient (Haeberli, 1985; Driedger and Kennard, 1986; Haeberli and Hoelzle, 1995). The thereby applied principle of an inverted flow law (shear stress and, hence, glacier geometry as a function of strain rate governed by overall mass flux as determined by topographic and climatic conditions) made it possible to model glacier thickness as a function of surface slope for all size categories. Corresponding 3-D-information is contained in, or can be derived from, detailed glacier inventories, or from modern glacier inventories combined with DEMs (Digital Elevation Models). Figure 2 shows a stress/elevation–range

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relation based on geometric data from glacier forefields exposed since the Little Ice Age as a consequence of glacier retreat: an important additional new source of world-wide data on glacier geometries for testing and validating 3-D-slope/elevation-related estimates of glacier thickness.

In contrast to 2-D- (planar) area-related estimates, 3-D slope-related approaches are not limited to average thicknesses of entire glaciers. A number of modern approaches at various levels of complexity have been recently developed (Clarke et al., 2012; Farinotti et al., 2009; Huss and Farinotti, 2012; Linsbauer et al., 2009, 2012; Paul and Linsbauer, 2012), which use high-resolution digital terrain information to provide quite detailed and realistic glacier-bed topographies. Such glacier-bed topographies also represent emerging topographies of new/future landscapes developing with continued glacier disappearance. An example is the modelling of glacier-bed overdeepenings as possible sites of future lake formation for thousands of glaciers in the Himalaya–Karakoram region by Linsbauer et al. (2016; cf. also the lower graphs in Fig. 1 relating to all glaciers in the Swiss Alps) or distributed thickness estimates for all glaciers in the world at the level of individual glaciers (Huss and Farinotti, 2012; Huss and Hock, 2015).

Calculated local ice thickness values can be directly compared to local ice-thickness information from field measurements and, hence, can be used to effectively calibrate/validate models (cf. conclusions 1 and 4 in Gärtner-Roer et al., 2014). The uncertainty of absolute thickness values seems to be lower than with area-related estimates but still remains high (on average about $\pm 30\%$ for individual glaciers as compared with local radio-echo soundings, cf. Linsbauer et al., 2012, and possibly around ± 10 to 20% for glacier ensembles; cf. Gärtner-Roer et al., 2014 and the perhaps somewhat overoptimistic estimate by Farinotti et al., 2009). The inter-comparison of model results provided for the Himalaya–Karakoram region by Frey et al. (2014) shows that average glacier thickness values calculated for large glacier samples from flux-driven approaches (Huss and Farinotti, 2012), which require a large number of assumptions about glacier mass balance and flow, are in agreement with much simpler/faster stress-

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driven approaches (Linsbauer et al., 2009, 2012) even within the uncertainty range (± 5 –10 m) of ice thickness determinations from field measurements (cf. also corresponding estimates by Andreassen et al., 2015). The latter approach especially lends itself to rapid local calibration/adaptation using field measurements and DEMs. Open questions and possibilities for further improvement exist. Examples are the appropriate treatment of flat firn divides or of debris-covered glacier tongues which may be far out of equilibrium.

The basal shear stresses used or calculated in slope-related approaches can be compared with values reported in the literature from detailed field measurements and can help to keep the problem of thickness overestimates for glacier complexes under control. Comparison between average basal shear stresses can also help with checking the plausibility of results from different approaches. Haeberli and Hoelzle (1995) and later Linsbauer et al. (2012) empirically set an upper-bound value of 150 kPa for the average basal shear stress in large glaciers (cf. Fig. 2 and shear stress values reported by, for instance, Eisen et al., 2005; Huss and Farinotti, 2012; Li et al., 2012). The glacier volumes calculated by Farinotti et al. (2009) for the Swiss Alps or by Huss and Farinotti (2012) for the European Alps are some 20 to 30 % larger than those estimated on the basis of a 150 kPa upper-bound-value for average basal shear stresses (cf. Linsbauer et al., 2012). Such high volumes may imply average basal shear stresses for larger glaciers around 180 to 200 kPa, which seems rather high or at least to constitute an upper limit (Fig. 2; cf. Fig. 9 in Frey et al., 2014). The parameterisation for the volume–area approach applied by Radić and Hock (2011; cf. Table 2 in Huss and Farinotti, 2012) produces more than 50 % higher values than this, indicating rather unrealistic average basal shear stresses in larger glaciers of about 200 to 300 kPa – the possibility of systematic overestimates cannot be excluded in this case. Values published by Raper and Braithwaite (2005) or Grinsted (2013) seem to be closer to a 150 kPa limit.

The remaining uncertainty, which is still considerable, is primarily due to the limits in our ability to understand and quantify the involved surface mass fluxes (especially

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accumulation) and the components of glacier flow (especially basal sliding) for un-measured glaciers – fundamental problems in glacier science, which remain difficult to overcome. Despite this limitation, 3-D-flux/stress/slope-related thickness estimates have great advantages over 2-D- (planar) area-related approaches even for calculating overall volumes in that they (a) markedly reduce the problem of glacier complexes because elevation is less sensitive to changes or misinterpretations of area, (b) essentially decouple area from thickness estimates for volume calculations, thereby avoiding the error-propagation problem inherent with area-related thickness estimates and volume calculations, (c) can be directly calibrated/validated with ice-thickness information from local field measurements, and (d) help with plausibility considerations regarding the shear stresses involved with the obtained thickness/volume values.

5 Conclusion and perspectives

Planar, 2-D area-related statistics concerning thicknesses of individual glaciers or glacier ensembles that span less than several orders of magnitude (i.e. the range of essentially all glacier sizes existing on Earth) can only be order-of magnitude estimates. With detailed slope information having become available in DEMs for most regions of the world, local to regional and global applications of 3-D flux/stress/slope-related estimates of distributed glacier thicknesses and corresponding volume calculations have become possible. They are better constrained by calibration with local field measurements and more coherent among approaches at various levels of complexity than 2-D- (planar) area-related statistics. Most importantly perhaps, they enable detailed glacier-bed topographies to be calculated and, hence, provide more promising possibilities than area-related statistics about average thicknesses. Results of 3-D-related procedures are available at local, regional and worldwide scales.

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been used to improve the text and to strengthen the argumentation. I thank all the colleagues who have discussed these matters with me over many years now.

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On area- and slope-related thickness estimates and volume calculations

W. Haeberli

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Table 1. Instantaneous thickness change Δh (m) and instantaneous volume change ΔV (10^6 m^3) as an artefact from area-related statistics in case of separating/coalescing partial glaciers. The case of two partial glacier components with variable size ratios is considered at the very moment when the last/first ice crystal joining the two components melts/gets in contact. The relation $h = 51.8A^{0.45}$ from Fig. 7a in Andreassen et al. (2015) is used to estimate mean glacier thicknesses and changes in mean glacier thicknesses, and to calculate total glacier volumes and changes in total glacier volumes for the joined/separated glaciers. For mid-size and large glaciers the artefacts are tens of meters in average glacier thickness and many millions of m^3 to several km^3 in volume. Such massive artefacts are avoided with slope-related calculation of glacier-bed topographies which do not change with separating or coalescing glaciers.

Total area A (km^2)	1		10		100	
h (m), V (10^6 m^3)	52	52	146	1460	412	41 250
	Δh	ΔV	Δh	ΔV	Δh	ΔV
Size ratio						
1 : 1	14	14	39	390	110	1103
2 : 1	13	13	35	352	99	9940
4 : 1	9	9	26	259	74	7390
10 : 1	6	6	15	154	44	5370

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On area- and slope-related thickness estimates and volume calculations

W. Haeberli

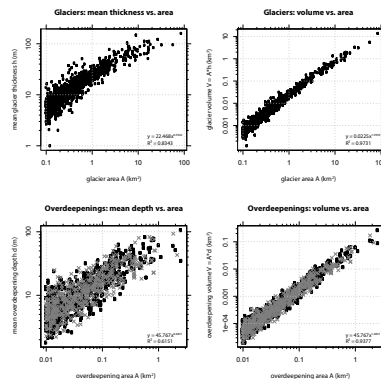


Figure 1. Areas (A), mean thicknesses (h) and volumes (V) of the Swiss glaciers (upper graphs) calculated from glacier-bed topographies modeled using GlabTop (Linsbauer et al., 2012). Even with a uniform calculation technique, mean glacier thickness as a function of glacier area (left) shows a scatter of roughly an order of magnitude for small glaciers and about half an order of magnitude for larger glaciers (the scatter would be even larger with glacier thicknesses derived from scarce field measurements and variable inter-/extrapolation techniques): glacier area is not a good predictor of glacier thickness. This problem is hidden in the self-correlation between glacier volumes ($V = A \cdot h$) and the glacier areas (A) from which these volumes had been calculated (right): the increase in the correlation coefficient, the good-looking graph and the generation of multiple orders of magnitude in the volume–area relation are artefacts produced by the use of glacier area in both variables of the regression and in both axes of the scatter plot. Multiplying the independent variable A with h produces $V = A \cdot h$, $R^2 = 1.0$; eliminating the common A in both variables eliminates the independent variable. The lower graphs illustrate similar effects for glacier-bed overdeepenings (from the same sample and model calculation; Linsbauer et al., 2012), which may become future lakes if exposed as a consequence of continued glacier recession and thinning. Graph and statistics provided by A. Linsbauer.

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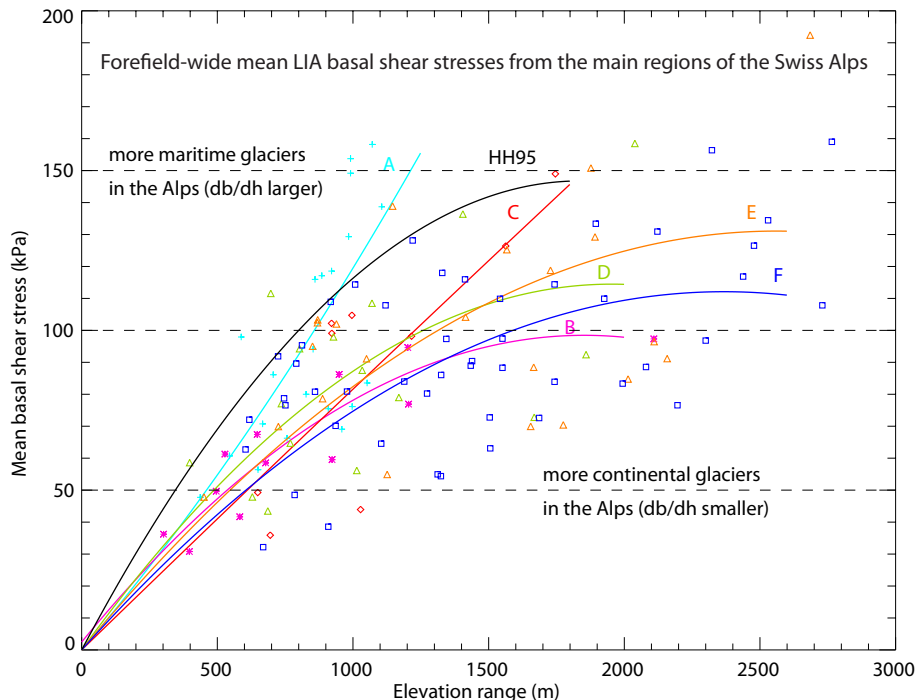


Figure 2. Average basal shear stresses determined from geometric information contained in glacier forefields and Little Ice Age moraines in the Swiss Alps as a function of the elevation range of the corresponding glaciers. Note the relation between average shear stress and elevation range and probably also with mass balance gradients (higher for glaciers in more humid-maritime than in dry continental climatic conditions). The scatter is large but generally remains within about $\pm 50\%$ of the mean. Maximum stress values are around 150 kPa with an exceptional value near 200 kPa. A = Central Grison Alps, B = South Grison Alps, C = Glarus Alps, D = Central Swiss Alps, E = Bernese Alps, F = Valais Alps, HH95 = Haeberli and Hoelzle (1995). Adapted from Fischer (2012; cf. Fischer et al., 2013). Reproduced with permission.